Design of an Underground Facility
Subjected to CWE and Accidental Threats

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Abstract: A preliminary design of a large underground facility was performed. The hardened design requirements for this facility include: penetration and ground shock due to conventional
weapon effects (CWE) and impact induced ground shock due to accidental aircraft crashes. CWE threats used for the preliminary design included a 450-kg general purpose bomb and a 210-kg earth penetrating bomb. Possible accidental aircraft crash scenarios were identified based on a survey of available crash data for large commercial and military fighter aircraft. From these crash scenarios, worst case and most probable impact cases were identified. Design conservative ground shock predictions were performed. Structural response calculations using these ground shock predictions were performed to determine structural sizes and shock isolation requirements. This paper summarizes scoping calculations performed in support of the design
effort.

INTRODUCTION

A large underground facility was designed by the US Army Corps of Engineers (COE), Omaha District. The structure was approximately 200 meters wide by 200 meters long in plan with the width of the structure divided into narrow bays that ran nearly the entire length of the structure. This facility was designed to resist several external threat scenarios including bomb threats and accidents involving aircraft crashes. Design response limits were conservatively specified as 2 degrees rotation for CWE and 4 degrees rotation for impact induced ground shock loads.

Scoping calculations were performed to support the COE's design as follows:

- calculate CWE for generic 450-kg general purpose (GP) and 210-kg penetrating bombs
- design the penetration mitigation system to protect the structure from CWE
- perform structural response parameter studies to proportion structural members and investigate in structure shock
- develop aircraft crash scenarios for a large commercial airc raft and a military fighter aircraft
- define impact induced ground shock loads from selected crash scenarios
- evaluate the structure subjected to crash loads.

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General structural details were specified by the sponsor in the beginning of this project. Known details included:

- clear span of 4.2 meters
- clear height of 6 meters
- interior structural wall thickness of 0.8 meter
- dynamic t ensile strength of reinforcing of 472.3 Mpa

Details that were unknown or uncertain were (with limits in parentheses):

- roof, floor, and exterior wall thickness (0.8 to 1.2 meters)
- dynamic concrete compressive strength (34.5 to 48.3 Mpa)
- principal reinforc ement ratios (0.0025 to 0.01 each face)
- burster slab thickness (1 to 2 meters)
- depth of soil cover - distance between bottom of burster slab and top of structure (4 to 6 meters)

Due to time limitations, the approach was to perform the CWE design in parallel with the development of the crash scenarios and check the resulting CWE design with crash induced ground shock loads.

This paper summarizes the preliminary scoping calculations performed to determine the structural requirements to resist the CW threats and the worst case crash scenarios (References 1 and 2).

PRELIMINARY CWE DESIGN

The CWE threats were defeated by a combi nation of penetration mitigation to keep the bombs a safe distance away from the structure and hardening the structure to survive a stand-off detonation.

Structural response calculations for this task were performed using the In-Structure Shock (ISS) computer program (Reference 3). ISS is a plane frame finite element model developed specifically for the design and analysis of hardened structures subjected to conventional weapon detonations. ISS uses a lumped mass formulation and explicit time integration (central difference). Externally applied nodal forces are derived from Structure-Medium Interaction (SMI) boundary elements loaded by the free-field stress and velocity fields. The free-field loads are calculated for each node at each time step. The internal CWE drivers include simple TM5-855-1 design manual free-field predictions for airblast on aboveground structures or ground shock on below-ground structures. In addition, more accurate free-field ground shock predictions developed from analytical fits to large scale finite element calculations, such as those produced by the WES SABER (Reference 4) ground shock code are available for a number of representative backfill materials. A driver for ISS, FOIL (Reference 5), was developed to fit, reproduce, and scale the results of the SABER free- field ground shock calculations. The ISS computer program is easy to use in a competent manner and is computationally efficient so that large numbers of parameter studies can be readily performed. ISS fills the void between simplified single-degree-of-freedom idealizations of a

complex SMI problem and the more robust solutions afforded by large general purpose 3-D finite element codes. The development work for the ISS code was in support of the Defense Nuclear Agency (DNA)/Waterways Experiment Station (WES) In-Structure Shock research program.

Penetration calculations to size the burster slab thickness and the extent of the burster slab were performed primarily with the PENCURV computer program (Reference 6). The PENCURV code is a 2-D projectile penetration code developed by WES that considers the penetration of a rigid projectile into a layered media. Forces imparted to the projectile as it penetrates are summed over the projectile surface area and the equations of motion are solved numerically.

Parametric calculations of ground shock and structural response to establish the depth-of-burial
and structural section details for four CWE cases were performed. The cases were combinations of two bomb impact locations and two weapons as shown in Figure 1. The soil backfill properties were unknown but were assumed to be bounded by flume sand and clay from the FOIL database. The CWE threats for this task were defined as:

- 450-kg general purpose (GP) bomb
  expl osive weight - 168 kg H-6 equivalent
  length - 2 meters
  diameter - 0.36 meters

- 210-kg earth penetrating (EP) bomb
  explosive weight - 47-kg H-6 equivalent
  length - 1.42 meters
  diameter - 0.25 meters

Exterior structural member thicknesses of 0.8, 1.0, and 1.2 meters were used. Burster slab thicknesses of 1.1, 1.5, and 2.0 meters were used in the penetration calculations. For this parameter study a baseline dynamic concrete strength of 41.4 MPa (6000 psi) for structural elements was used. Concrete strength was varied from 34.5 to 48.3 MPa for the structural response calculations to cover the possible ranges of dynamic strength expected. Interior wall thicknesses were maintained at constant values of 0.8 meter for the primary structural walls with 0.25% reinforcement in each face. The concrete compressive strength for the interior walls was varied to agree with the exterior walls and the floor and roof slabs in each analysis. Principal reinforcement for the exterior walls and the roof and floor slabs were varied from the baseline value of 0.25% each face to 0.375% and 0.5%.

The burster slab was assumed to be 1.5 meters thick for bomb placement and depth-of-burial in the structural response calculations.

Figure 1. Structure-Bomb Configuration for Parametric Studies.
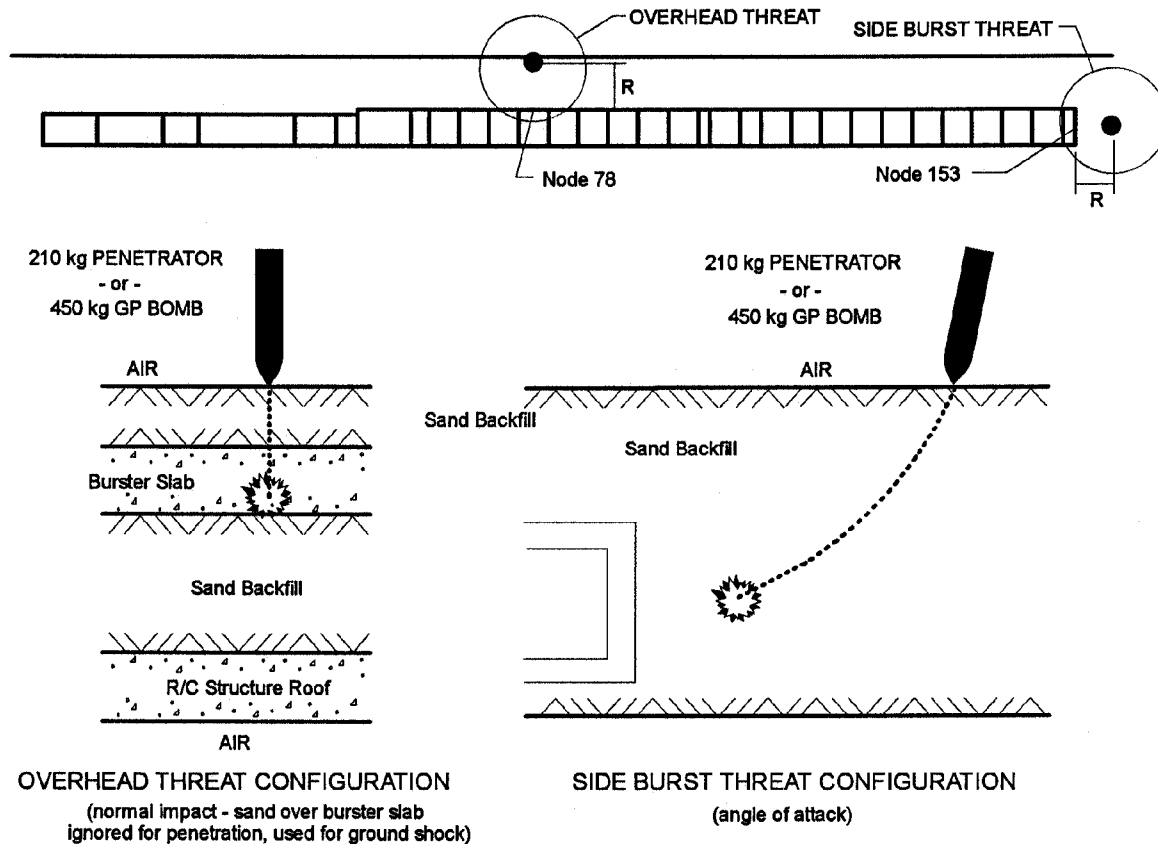
Figure 1. Structure-Bomb Configuration for Parametric Studies.

Examples of the radial free-field time histories at several ranges (5, 6, 7, and 8 meters) are shown in Figure 2. The fit parameters used in the FOIL prediction were based on a SABER calculation using CONWEB Sand (Reference 5), a flume sand used in a small scale CWE test (Reference 7) performed by WES. The CONWEB Sand has a density of 1865 kg/m3 and a primary loading wave velocity of 400 m/s. A comparison of the FOIL predictions to the observed data from CONWEB Test 3 is shown in Figure 3. The FOIL driver matches the peaks and the waveforms quite well. As a worst case estimate of the ground shock environment, a limited set of calculations was performed using the CONWEB Clay (Reference 5) material properties. The CONWEB Clay has a density of 1967 kg/m3 and a primary loading wave velocity of 190 m/s. It was considered an unlikely upper bound for the free-field environment prediction.

Figure 2.
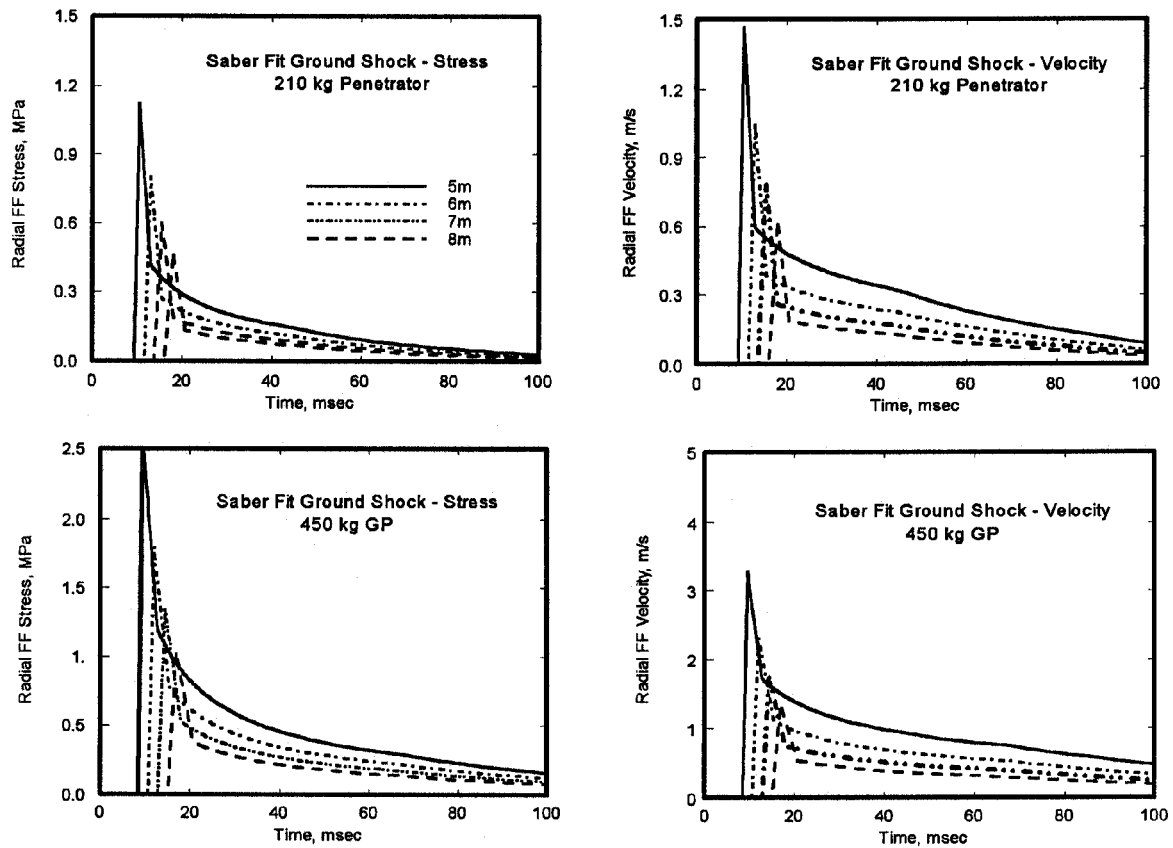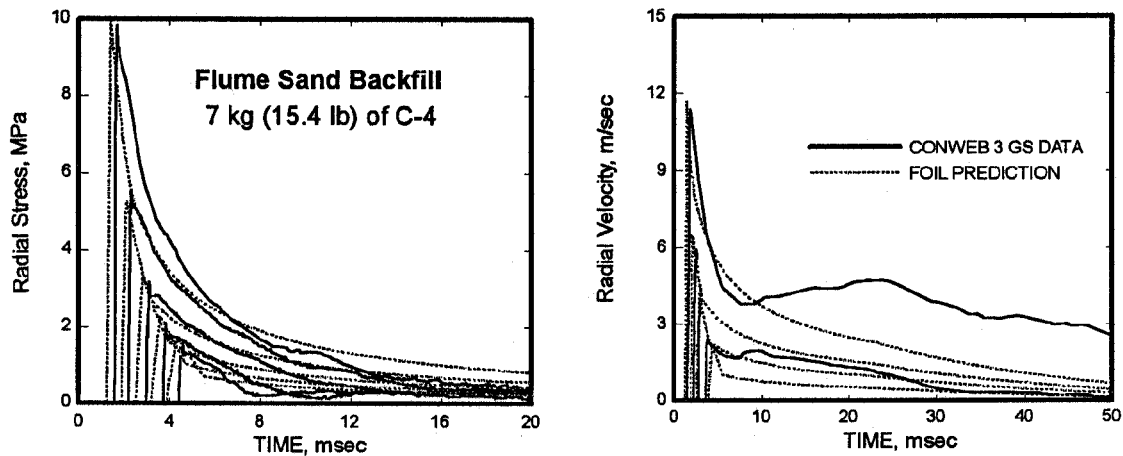## FOIL Ground Shock Prediction for the 450-kg GP and the 210-kg EP.

Figure 2. FOIL Ground Shock Prediction for the 450-kg GP and the 210-kg EP.

Figure 3.
Comparison of FOIL Predictions with CONWEB 3 at 0.9 to 2.1-meters.

Figure 3. Comparison of FOIL Predictions with CONWEB 3 at 0.9 to 2.1-meters.

A planar section of the structure was modeled for use by the ISS code as shown in Figure 4. The structure was represented by 471 elements defined by 441 nodes. Centerline dimensions were used in building the model even though this underpredicted the structural resistance (design conservative). No nodal restraints were imposed on the model (rigid body motion of the structure was allowed). The baseline structural configuration consisted of 1 meter exterior sections, 41.4 MPa concrete, and 0.25% reinforcing each face.

Figure 4. ISS Model of Facility for Ground Shock Analysis.
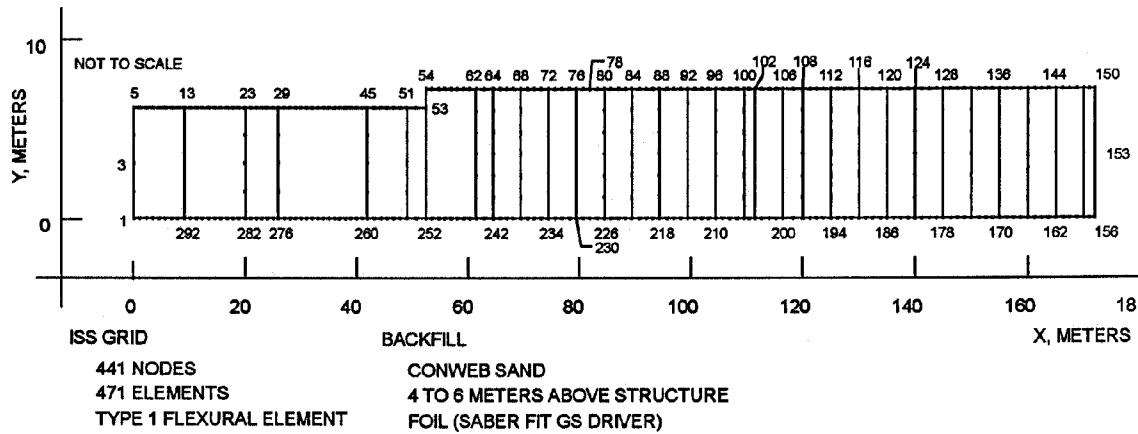
Figure 4. ISS Model of Facility for Ground Shock Analysis.

Side burst detonations were located at the elevation of the midheight of the right wall (Node 153, Figures 1 and 4) at standoffs ranging from 2.5 to 6 meters for the GP and 2 to 4 meters for the EP. The weapons were fully coupled for these calculations. The results are presented in Figure 5. For the design criteria of 2 degrees of support rotation, the critical standoff for the GP was 3.7 meters for the 41.4 MPa concrete strength with a variation of 0.1 meter for the higher and lower concrete strengths. This is an insignificant variation in response as a function of concrete strength. Similarly, the effect of changing reinforcement ratio was small for the GP side burst case as shown in Figure 5. A change in standoff of approximately 1 meter (3.2 to 4.2) was noted when the wall thickness was changed from 0.8 to 1.2 meters. Figure 5 also shows that the EP is not a significant side burst threat to the structure if it is prevented from detonating less than 2 meters from the wall in sand backfill.

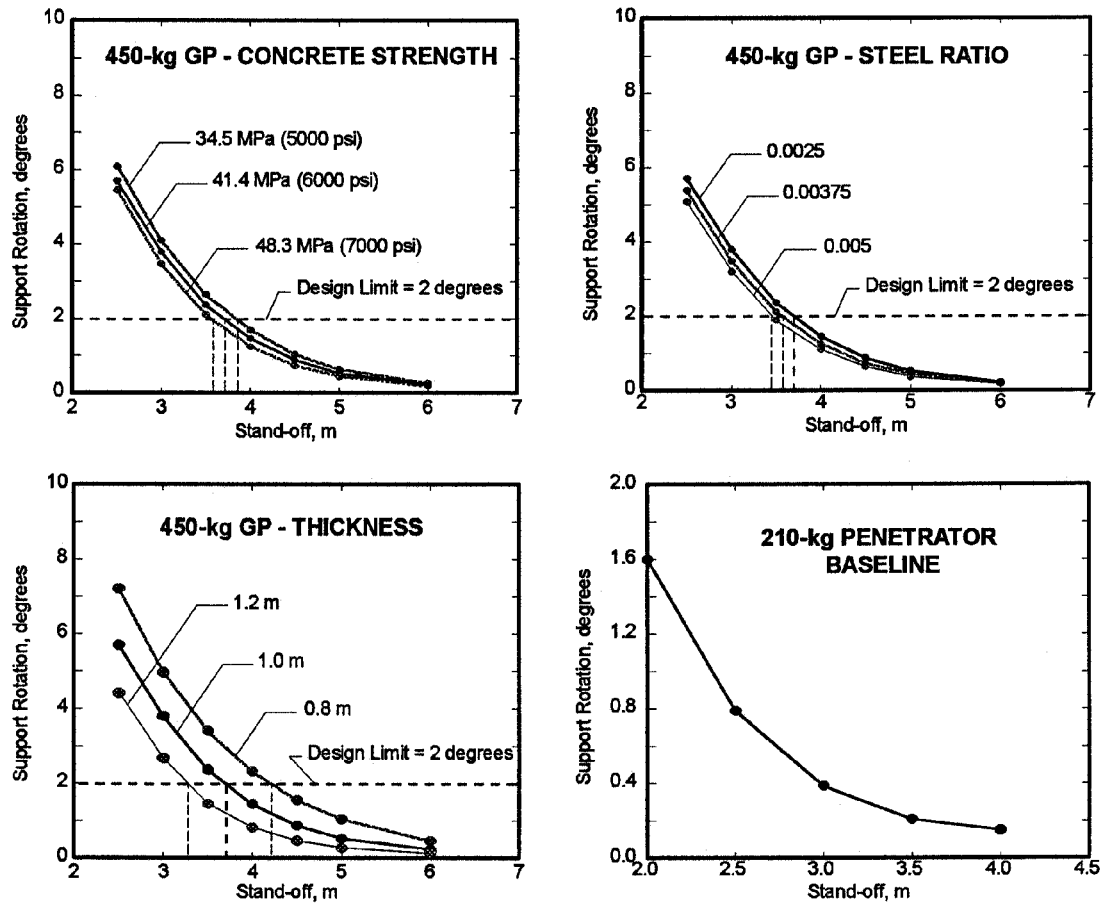**Figure 5. CWE Results for the Side Burst Case.**

Figure 5. CWE Results for the Side Burst Case.

In sand backfill, neither the GP or the EP were significant overhead threats to the structure even at the shallowest depth-of-burial (4 meters of soil plus burster slab) and with the thinnest roof slab (0.8 meter) provided the burster slab was not penetrated by the weapon. Response was elastic. If clay backfill was used instead of sand, a soil layer thickness of 4.8 meters was required to maintain 2 degrees of support rotation in the critical roof element for the GP (governing threat).

REVISED CWE DESIGN

The floor plan was revised by the sponsor near the completion of the parameter study to include:

- clear span of 3.2 meters(32 bays)
- clear height of 4.7 meters
- interior structural wall thickness of 0.8 meters for each bay (steel ratios of 0.0025 each face)
- roof and floor thickness of 0.7 meter (steel ratios of 0.005 each face)
- exterior wall thickness of 1.0 meter (steel ratios of 0.005 each face)
- dynamic concrete compre ssive strength of 41.4 MPa (6000 psi)
- dynamic tensile yield strength for reinforcement of 472.3 MPa (68,500 psi)

A series of ISS CWE calculations was performed to evaluate the revised structure. The controlling CW threat from previous calculations was the 450-kg GP bomb; therefore, only the GP was used in these analyses. Bomb location for the overhead threat was above node 119 as shown in Figure 6. Two bomb locations were used for the side burst threat: at the elevation of the exterior wall midheight (Node 161), and at the elevation of the roof slab (Node 159).

Figure 6. Bomb Placement for the Revised Structure.
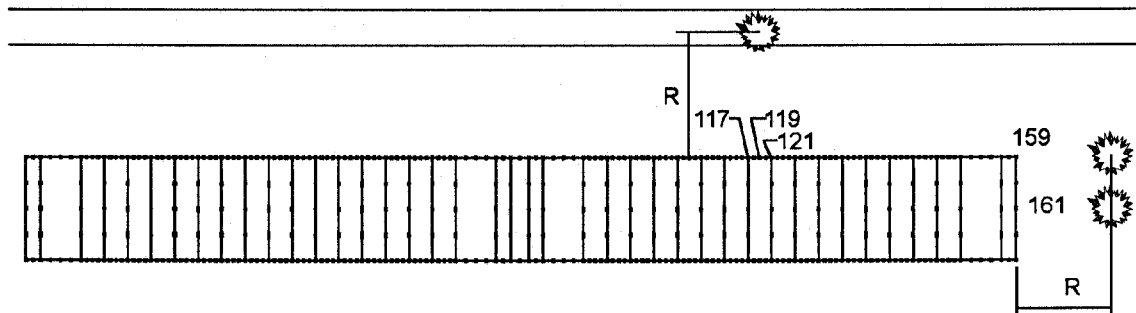
Figure 6. Bomb Placement for the Revised Structure.

For the overhead threat the GP bomb was placed above the revised structure at standoffs of 4 to 7 meters. This range of standoffs corresponds to 3 to 6 meters of soil cover over the structure. Backfills considered were CONWEB sand and clay to bound the actual backfill expected at the facility site. Results of the analyses of the overhead GP bomb threat are presented in Figure 7. Even at a standoff of 4 meters the damage is less than the design allowable rotation of 2 degrees for sand backfill. The structural response was 2 degrees support rotation at a standoff of
approximately 4.9 meters (soil cover of 3.9 meters) in the clay backfill.

The bomb for the first side burst case was located at the elevation of the midheight of the wall (Node 161, Figure 6) at standoffs ranging from 2.5 to 6 meters. The critical standoffs (for 2 degrees support rotation) were 3.2 meters in sand backfill and over 6 meters in clay backfill as shown in Figure 7.

The bomb for the second side burst case was located at the elevation of the roof slab (Node 159, Figure 6) at standoffs ranging from 2.5 to 6 meters. The structure responded in a global flexural mode (like a cantilever) in addition to local flexural response of the wall and of the closest roof span. The critical standoffs (for 2 degrees support rotation) were less than 2.5 meters in sand backfill and 5.9 meters in clay backfill as shown in Figure 7. This information along with the results from the preceding paragraph for the side burst at midheight of the wall and the results of side impact penetration calculations was used to estimate the extent of the burster slab.

Figure 7. CWE Analysis Results for the Revised Structure
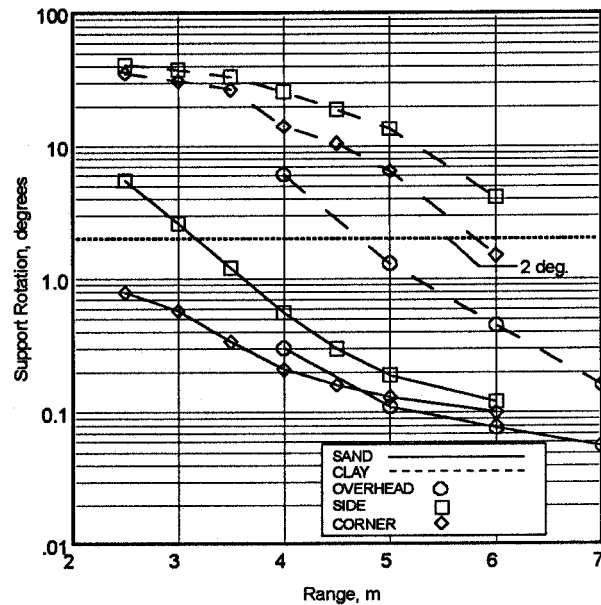
Figure 7. CWE Analysis Results for the
Revised Structure.

CWE PENETRATION MITIGATION

The adequacy of 3 burster slab thicknesses, 1.1, 1.5 and 2.0 meters was investigated using PENCURV. In addition, the TM5-855-1 (Reference 8) and the ESL-TR-87-57 (Reference 9) requirements for defeating the penetration threat were determined as a check on the PENCURV analyses. The 1-meter soil cover above the burster slab was neglected for these penetration calculations. The side impact cases were investigated to determine the extent of the burster slab beyond the edge of the structure to maintain a safe stand-off for structural response due to ground shock.

Figure 1 shows the layered model used in the PENCURV calcul ations. The burster slab thickness was varied from 1.1 to 1.5 and 2.0 meters. Concrete strength was assumed to be 20.7 MPa (3000 psi, no increase from static value). Impact velocities ranging from 180 to 335 m/s (600 to 1100 f/s) were considered even though the 450-kg GP may break up at less than 335 m/s. The thin burster slab (1.1 meter) was easily penetrated by the 450-kg GP at all impact velocities. The 2-meter slab stopped the EP at all impact velocities of interest. The 1.5-meter burster slab stopped the GP at impact velocities less than 245 m/s (805 fps). This means that the 1.5-meter burster slab is adequate for most impact velocities of interest since the worst case of a normal impact was assumed. The 1.5-meter burster slab is adequate to defeat the GP overhead impact threat. Design manual methods required 1.6 to 1.7 meters of concrete (considering dynamic concrete strength of 27.6 MPa) to prevent penetration by the

GP. The GP was again the governing threat. Higher impact velocities were considered for the EP against the 1.5 meter slab. A 1.5-meter slab is marginally adequate up to a normal impact by the EP of 305 m/s provided a dynamic concrete strength of 27 MPa is used.

To determine the extent of the burster slab to protect the structure from a weapon detonation at a standoff from the side and end walls, a series of PENCURV calculations was performed for the GP and the EP. The impact velocity selected for the GP was 274 m/s (900 f/s). The generic 450-kg GP was modeled with the WES recommended geometry. The WES geometry includes a maximum diameter of 0.36 meter (1 meter from the tip) tapered to 0.33 meter at the tail. The angle of attack was varied in 5-degree increments from normal, 0 degrees, to 40 degrees. Sand backfill used was assumed to have a Sandia "S" value of 5. S is an empirically determined soil penetrability constant based on fits to penetration data in various soils. S values given in Reference 9 for medium dense, medium to coarse, wet or dry sand with no cementation ranged from 4 to 6. An S value of 5 was selected as a midrange design estimate. S values of 4 to 12 could be used depending upon soil at the site selected.

The point of impact for the GP was determined by superimposing the burster slab on the penetration path plots as shown in Figure 8. Structural locations were determined by the depth of soil cover between the top of the structure and the bottom of the burster slab (4, 5, and 6 meters) and the critical standoffs for the GP bomb from the midheight of the wall (3.2 meters) and from the wall at roof level (2.5 meters). For the baseline case of 5 meters of soil cover (total depth of 7.5 meters), a burster slab extent of 6.8 meters past the edge of the structure is required.

If the soil layer between the burster slab and the structure is reduced to 4 meters, the required burster slab extent is increased to 9 meters. If the soil cover is increased to 6 meters, the burster slab extent is reduced to 6.5 meters.   A design conservative (sand backfill) burster slab extent of 9 meters past the structure moves the detonation location due to Path 7 (Figure 8) far from the top corner of the structure.

One possible scenario that must be prevented is: the GP bomb enters the ground, ricochets under the burster slab, and detonates between the burster slab and the structure. This is a far worse threat than the overhead penetration/detonation threat considered in the structural calculations earlier in this report. Paths 8 and 9 in Figure 8 represent this threat. Using PENCURV, the GP impacted soil and ricocheted. The GP hit the bottom of the burster slab and was stopped before it passed the edge of the structure. Paths 8 and 9 are not governing cases for the three burial configurations considered in this study. Bomb placement due to paths 7, 8, and 9 should be investigated in more detail.

**Figure 8.
Side Impact Penetration for the 450-kg GP at 274 m/s in Sand Backfill.**
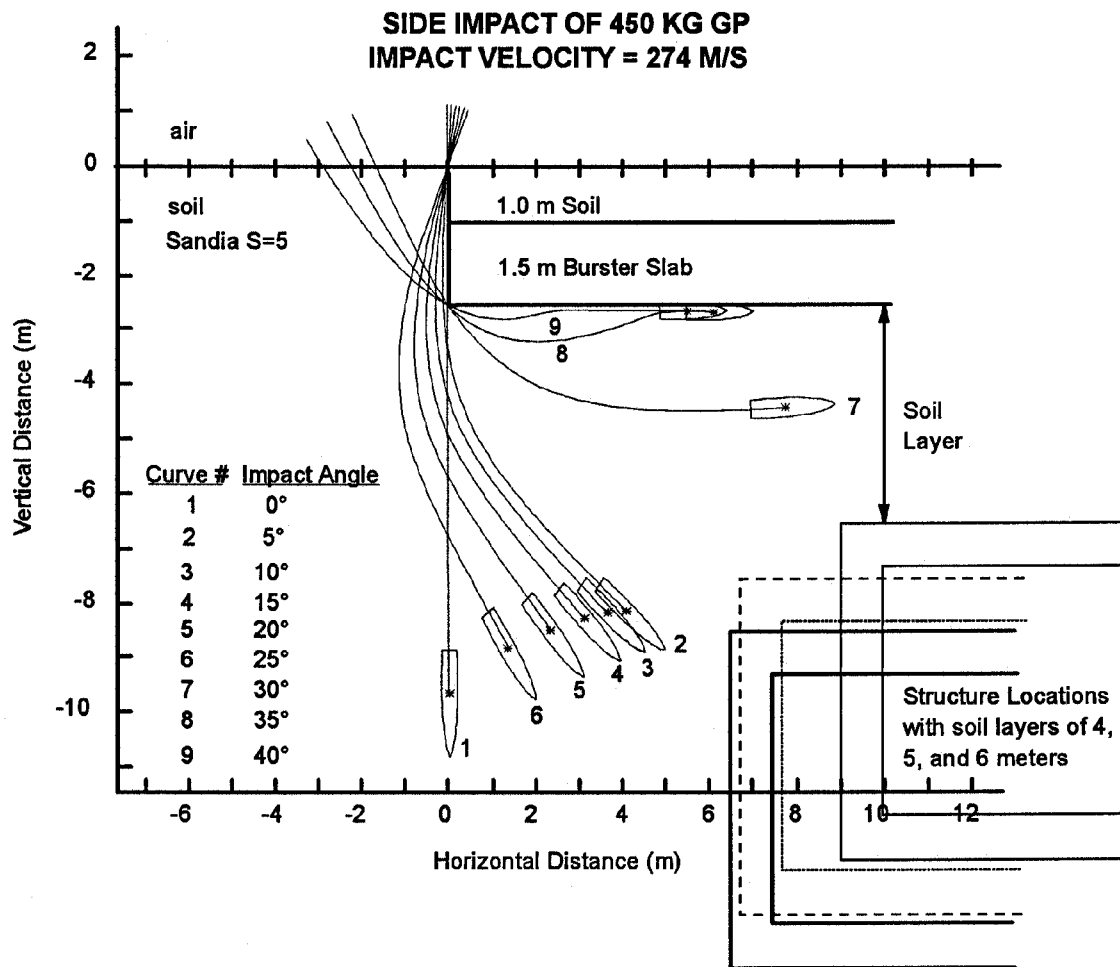

Figure 8. Side Impact Penetration for the 450-kg GP at 274 m/s in Sand Backfill.

A similar analysis was performed for the 210-kg EP at an impact velocity of 305 m/s. The maximum lateral penetration predicted was 5 meters past the edge of the burster slab at an elevation above the roof level of the structure. The burster slab extent of 6.8 meters (5-meter soil layer between burster slab and top of structure) determined by the GP penetration analysis above is adequate for the 210-kg EP.

If the backfill type is changed to something other t han the sand chosen, the side impact threats must be reevaluated. The burster slab extent design is not conservative for clay.

CRASH SCENARIOS

A study was performed to estimate impact velocities for a large commercial plane and a military fighter for the theoretical worst case, documented worst case, and most probable crash scenarios (Reference 2). The theoretical worst case crash for the large plane was a normal impact (400,000 kg - plane fully loaded including fuel) at 271 m/s. The worst documented crash was a normal impact at 224 to 255 m/s of a plane section consisting of the wings and the fuselage between the wings (136,000 kg). The estimated most probable impact was the entire plane (400,000 kg) at 10 m/s with an angle of inclination of 5 degrees off horizontal (crash landing). Only worst case theoretical estimates for the fighter could be made. A 775 m/s normal impact of 36,000-kg mass was identified as the worst case fighter impact.

Estimates of impact induced ground shock were used to d rive ISS calculations of structural response of the facility. The first approach used an equivalent HE source to approximate impact loads. The equivalent HE yield for an overhead impact was increased until roof support rotations reached 4 degrees. After determining the allowable weapon yield, estimates of allowable impact velocities for the large commercial plane and the military fighter were determined by equating the kinetic energy of the plane and the HE yield that produced the specified structural response. Using this method and the maximum soil layer thickness of 6 meters plus a 1.5-meter burster slab (the 1-meter soil layer above the burster slab was ignored) maximum impact velocities of 225 m/s for the large plane and 738 m/s for the fighter result in the design limit of 4 degrees of support rotation for the roof slab of the structure (0.7-meter thick roof - revised configuration). This approach indicates the structure will not satisfy the design response requirements for the worst theoretical plane impacts. The worst documented case (136,000-kg plane section at 224-255 m/s) results in an acceptable support rotation of 3.5 degrees. The most likely crash (10 m/s) is also survivable.

The second approach was to model several aircraft impacts with a 2-D finite element code, HONDO. The aircraft impact was modeled as an initial value problem. The plane mass, in contact with the top of the burster slab, was given an initial downward velocity equal to the impact velocity. The ground shock time histories from the finite element analyses were used as drivers for ISS calculations of structural response. The 2-D finite element model used in this study included the mass of the plane but not the deformation characteristics of the plane. The effect of this oversimplification is to increase ground shock peaks and decrease durations. The maximum impact velocity considered for the full mass of the large plane was limited to 129 m/s by the sponsor for 2-D FE calculations of the worst case impact. The worst case impact velocity for the fighter was 775 m/s for this study. A typical finite element grid of the fighter mass impact is shown in Figure 9.

Sand backfill was used beneath the burster slab. The crater formed by the fighter was approximately 6.5 meters deep as shown in Figure 10. An ISS analysis of the facility (6.5-meter soil cover and burster slab, 0.7-meter roof slab) was performed using the finite element ground shock predictions to drive the roof loads. A snapshot of the deformed grid is shown in Figure 11. Maximum roof support rotation was an unacceptable 8.5 degrees. The primaryresponse mode was a global flexural mode covering five bays rather than the more

local response modes observed in the GP and EP CWE analyses. A parameter study was performed to determine the required roof thickness to survive the fighter impact at 775 m/s. The required roof thickness was 1 meter for 4o of support rotation. The governing threat for the overhead plane impact was the fighter at 775 m/s. Complete details of the analyses of all plane impacts considered with ground shock loads and comparisons of the equivalent HE source and FE impact are given in Reference 1.

Figure 9. Finite Element Grid For Fighter Impact Ground Shock Calculation (axis labels in inches)
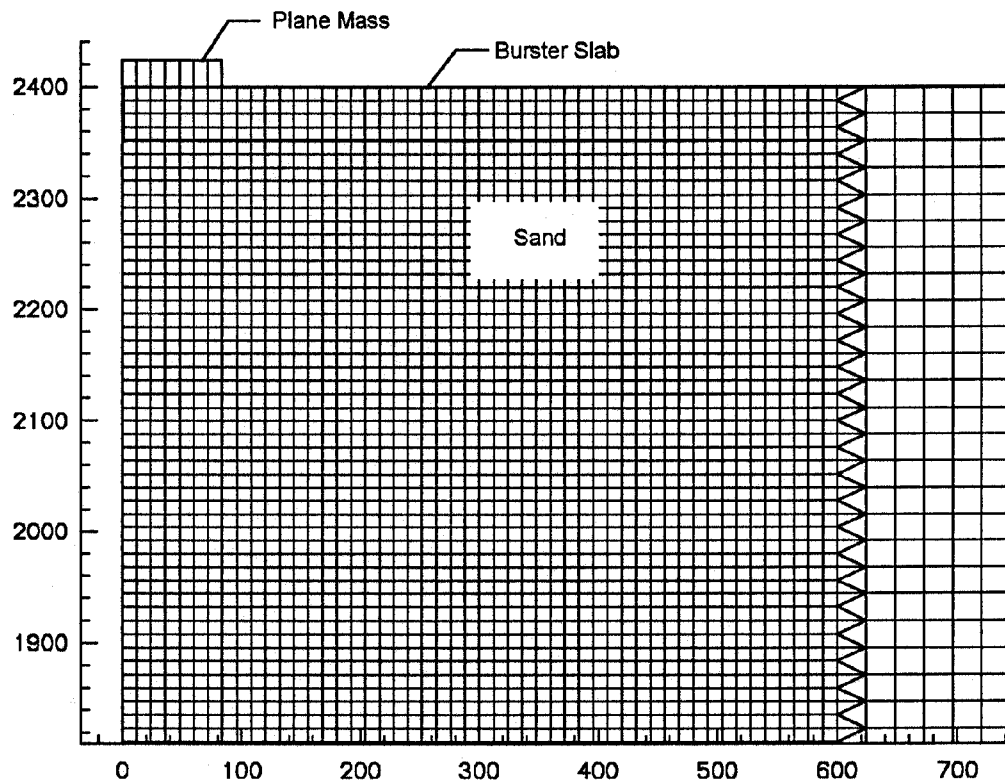
Figure 9. Finite Element Grid For Fighter Impact Ground Shock Calculation (axis labels in inches)

Figure 10.
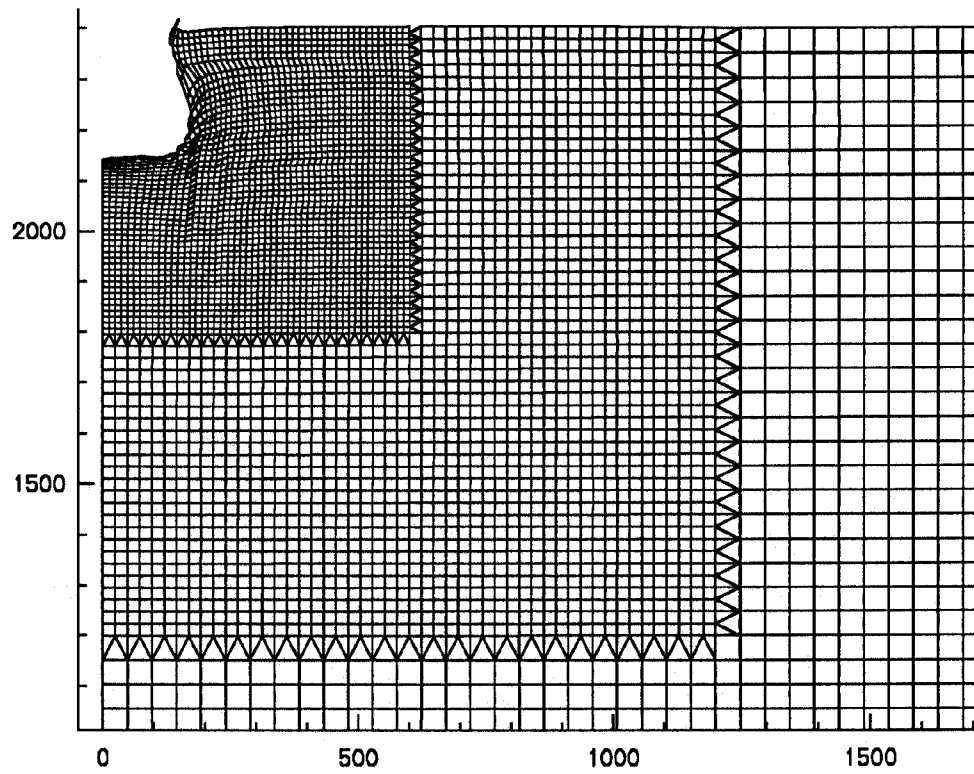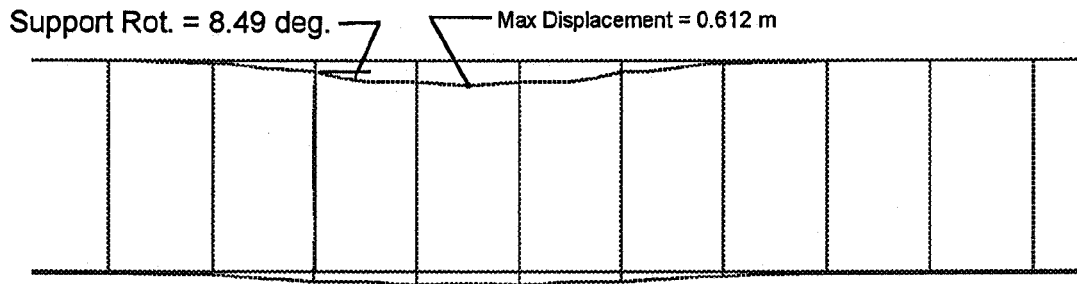**Deformed Mesh for the Fighter Impact Calculation (axis labels in inches).**

Figure 10. Deformed Mesh for the Fighter Impact Calculation (axis labels in inches).

Figure 11. Deformed ISS Grid for the Fighter Impact at 775 m/s.

Figure 11. Deformed ISS Grid for the Fighter Impact at 775 m/s.

STRUCTURE SHOCK

In the design of a hardened shelter,   the function of the shelter is as important as the structural integrity. The function of internal equipment may be compromised by high levels of in-structure shock. The overhead and sideburst GP threat was considered in computing in-structure shock at several locations along the floor of the facility. In-structure shock is typically presented in the form of shock spectra, plots of maximum responses (acceleration, velocity, and displacement) of linear oscillators subjected to input base motions. The velocity-time histories from ISS analyses for the floor nodes were used to drive an SDOF code to generate shock spectra.

Table 1 summarizes peak spectral responses for the 450-kg GP overhead and side burst cases and
the fighter overhead impact case. These spectral responses can be used in evaluating shock isolation requirements for facility equipment and containers.

Table 1. Peak Spectral Responses for the GP and Fighter Threats.

CASE	Horizontal			Vertical		
	Amax, g	Vmax, m/s	Dmax, mm	Amax, g	Vmax, m/s	Dmax, mm
GP-OH	30	0.2	0.5	150	1.3	20
GP-SIDE	130	1.0	15.0	100	0.9	5
FIGHTER-OH	90	0.3	9.0	500	5.0	250

CONCLUSIONS AND RECOMMENDATIONS

An extensive preliminary parametric study was performed to evaluate the effects of structural thickness, reinforcement ratio, and concrete strength on required standoff that results in 2 degrees of support rotation for the 450-kg GP side burst and overhead burst. A limited number of calculations were performed for the 210-kg EP since the GP was the dominant CW threat. Overhead standoffs for the GP bomb for 2 degrees of support rotation ranged less than 4 meters in sand to 4.7 meters in clay. The wet clay backfill was used as an absolute worst case since backfill properties at the site was unknown during this project. For the side burst of the GP, allowable standoffs were 3.2 meters in sand and over 6 meters in clay. The burster slab should extend 6.8 meters past the structure to defeat the side burst threat in sand backfill. Soil material properties should be determined to better estimate the free-field ground shock.

The shelter design is governed by the overhead aircraft impacts due to the huge amount of kinetic energy associated with the commercial plane at 129 m/s and the fighter at 775 m/s. The baseline facility (0.7-meter roof) did not perform adequately when subjected to the simple models of the worst case crash scenarios. Additional work was performed to investigate thicker roof and floor slabs. The governing case for the roof and floor of the bays was the Fighter overhead impact at 775 m/s. The Fighter overhead threat required a slab thickness of 1 meter for 4o of support rotation. The proposed design included:

- clear span of 3.2 meters
- clear height of 4.7 meters
- interior structural wall thickness of 0 .8 meters for each bay (steel ratios of 0.0025 each face)
- roof and floor thickness of 1.0 meter (steel ratios of 0.005 each face)
- exterior wall thickness of 1.0 meter (steel ratios of 0.005 each face)
- dynamic concrete compressive strength of 41.4 MPa for all structural elements
- dynamic tensile yield strength for reinforcement of 472.3 Mpa
- burster slab thickness of 1.5 meters
- burster slab extent past edge of structure of 6.8 meters (9 meters is preferred) minimum if the backfill is sand
- dynamic concrete c ompressive strength of 27 MPa for the burster slab
- 5-meter sand layer minimum between top of structure and burster slab

These design recommendations should be verified with improved predictions of plane impact loads. A more rigorous crash model that considers a deformable plane should improve impact induced ground shock predictions.

ACKNOWLEDGMENTS

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